# Photon Structure and Photoproduction at HERA

Katharina Müller
Zurich University

on behalf of the H1 and ZEUS collaborations

Introduction

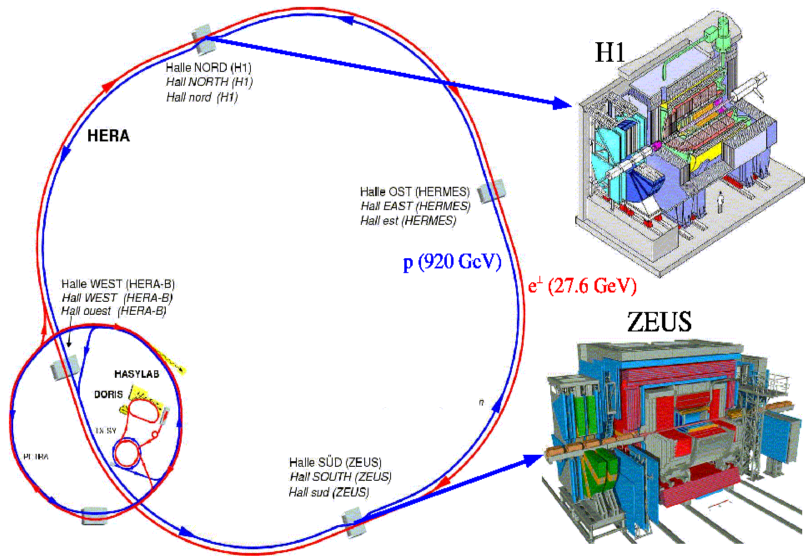
Dijet events
- QCD test
- Photon structure
- Transition Photoproduction to Deep Inelastic Scattering

Prompt Photons in Photoproduction

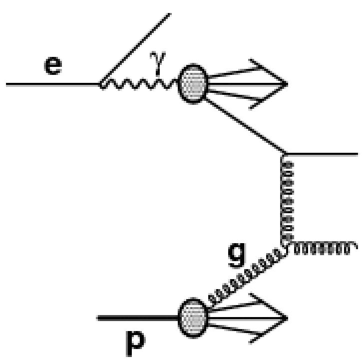
Final States in Photoproduction
- Diffractive Scattering of high t Photons
- Scaled Momentum Distributions

Photon2009, DESY, Hamburg, 11.-15. May 2009

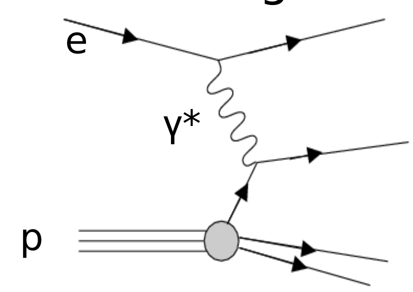
# HERA - Introduction




Photoproduction




Deep Inelastic Scattering




quasy real photon: $Q^2 \simeq 0$
Probe structure of the proton and photon

scattered electron not measured in main detector

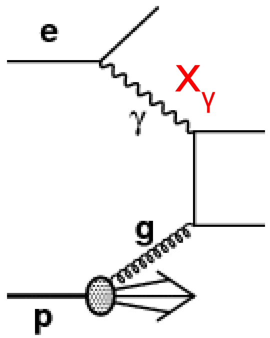
high photon virtuality $Q^2 >> 1\ GeV^2$
Probe structure of the proton

scattered electron in main detector

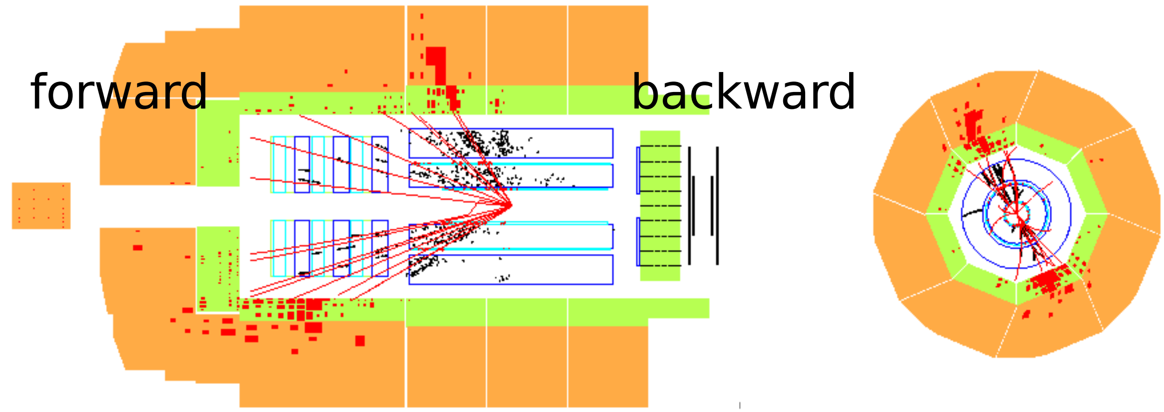
# Photoproduction at HERA - Introduction

LO: direct
photon interacts directly

$x_\gamma=1$

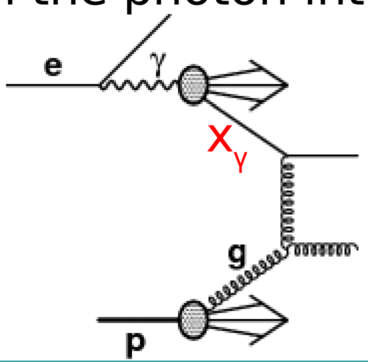


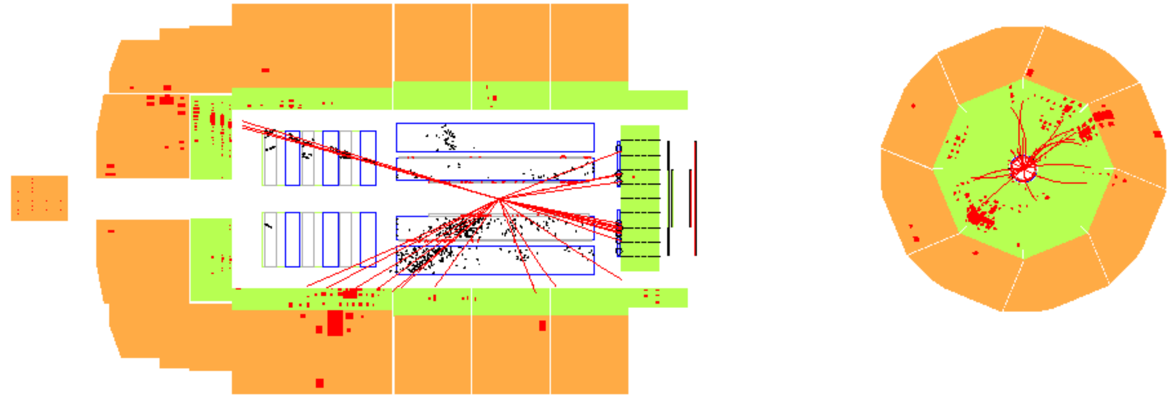

typical events with two hard jets




LO: resolved
partons from the photon interacts

$x_\gamma<1$



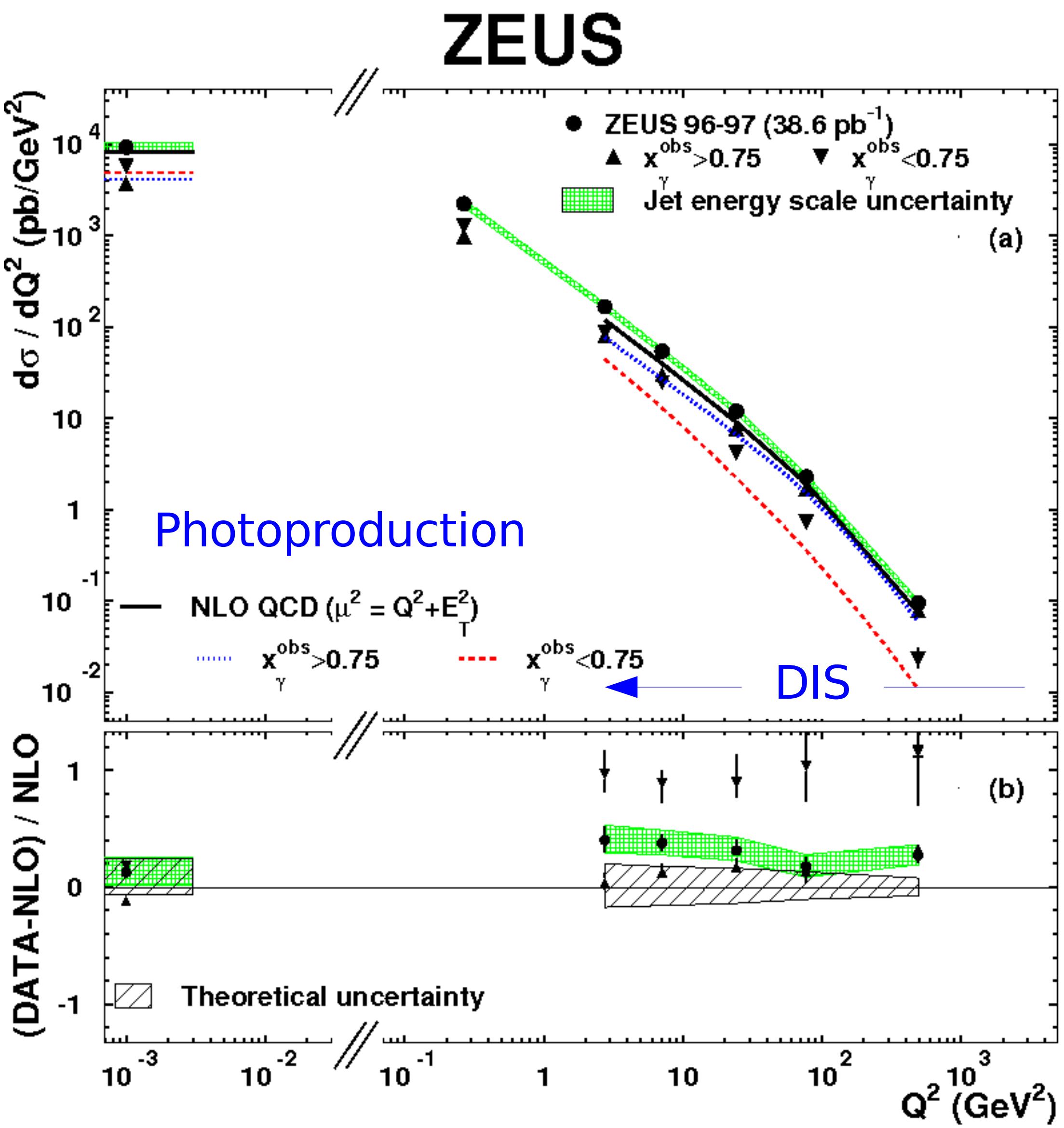



Probe structure of the photon with dijet events
$x_\gamma$ fraction of photon longitudinal momentum entering hard process

$$x_\gamma^{obs} = \frac{E_T^{jet1}\exp(-\eta^{jet1}) + E_T^{jet2}\exp(-\eta^{jet2})}{2\,y\,E_e}$$

Jets: inclusive kt algorithm

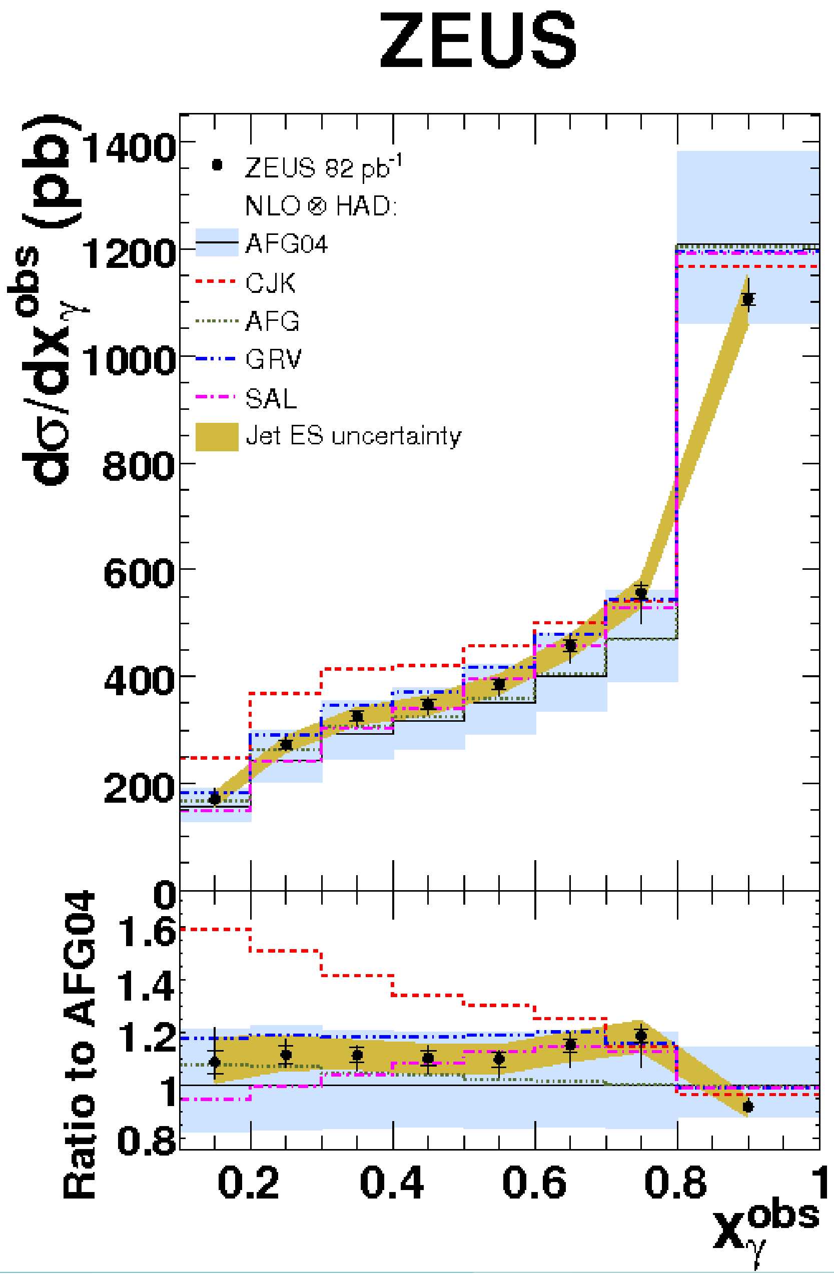
# $Q^2$ Dependence of Dijet Cross Section




- Cross section falls by 5 orders
- NLO describes shape, 30% low
- $x_\gamma^{obs} > 0.75$ well described
- $x_\gamma^{obs} < 0.75$
  - drops faster with $Q^2$
  - $Q^2 > 0$ underestimated by NLO
  - 25% contribution at high $Q^2$
  - NLO uncertainty higher (30%)
- $Q^2 = 0$ agreement with NLO
  - low $x_\gamma^{obs}$ dominant

hep-ex/0404033 ZEUS: 38.6 $pb^{-1}$ ,$0 < Q^2 < 2000$ $GeV^2$ jets: $-3 < \eta^{\gamma p} < 0$ , $E_T^{Jet1} > 7.5$ GeV, $E_T^{Jet2} > 6.5$ GeV

# Dijets in Photoproduction: Sensitivity to Photon PDF




$$x_\gamma^{obs} = \frac{E_T^{jet1} \exp(-\eta^{jet1}) + E_T^{jet2} \exp(-\eta^{jet2})}{2\, y\, E_e}$$

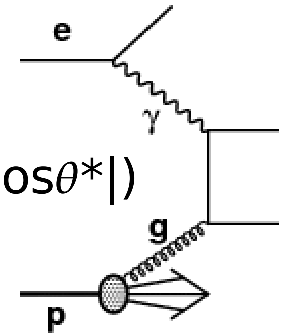
- Data: energy scale main syst. error
- High $x_\gamma^{obs}$
  predictions from different PDFs similar
- Low $x_\gamma^{obs}$
  Sensitivity to different photon PDFs

  differences up to 70%
- $x_\gamma^{obs} \gtrsim 0.8$ direct dominated
- $x_\gamma^{obs} \lesssim 0.8$ resolved dominated

arXiv:0706.3809 [hep-ex]] ZEUS: 81.8 pb-1, $Q^2<1$ GeV$^2$, $142<W^{\gamma p}<293$ GeV, $-1<\eta^{jet}<3$, $E_T^{Jet1}>20$ GeV, $E_T^{Jet}2>15$ GeV

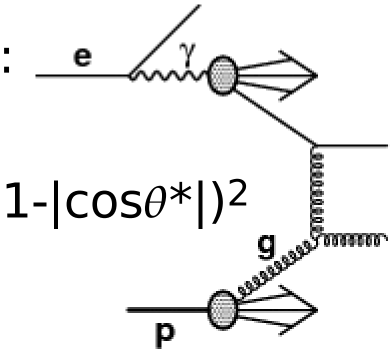
# Photon Structure – direct vs. resolved processes

Direct:



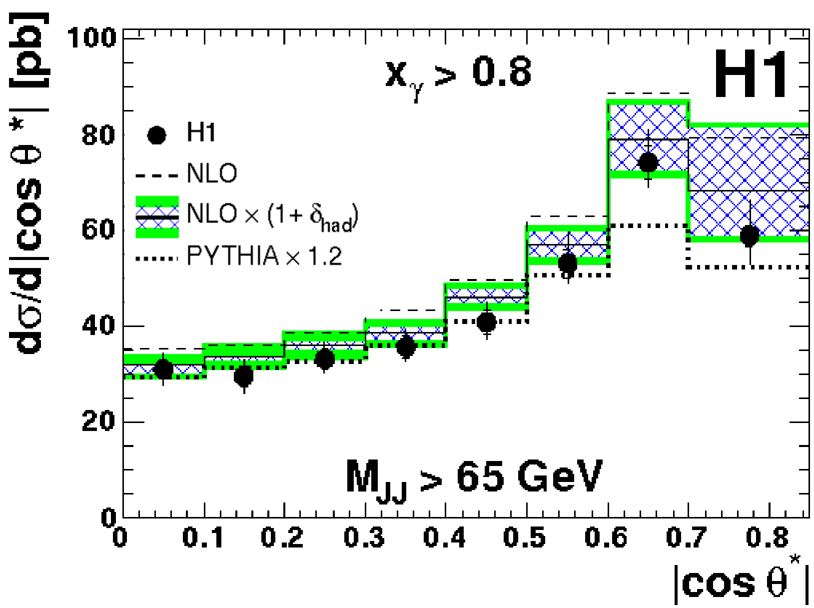

$1/(1-|\cos\theta^*|)$

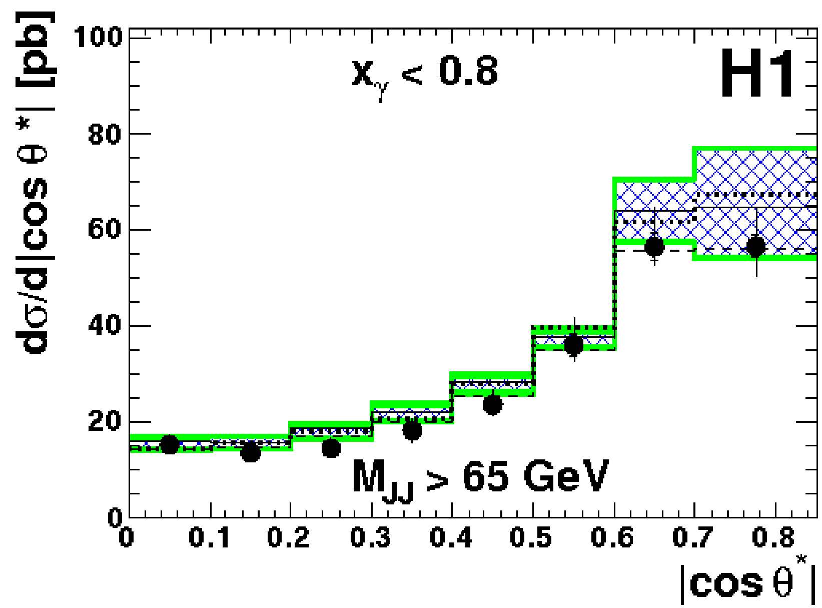
Resolved:




$1/(1-|\cos\theta^*|)^2$

CMS scattering angle $\cos\theta^* = \tanh((\eta^1-\eta^2)/2)$ sensitive to dynamics of hard interaction

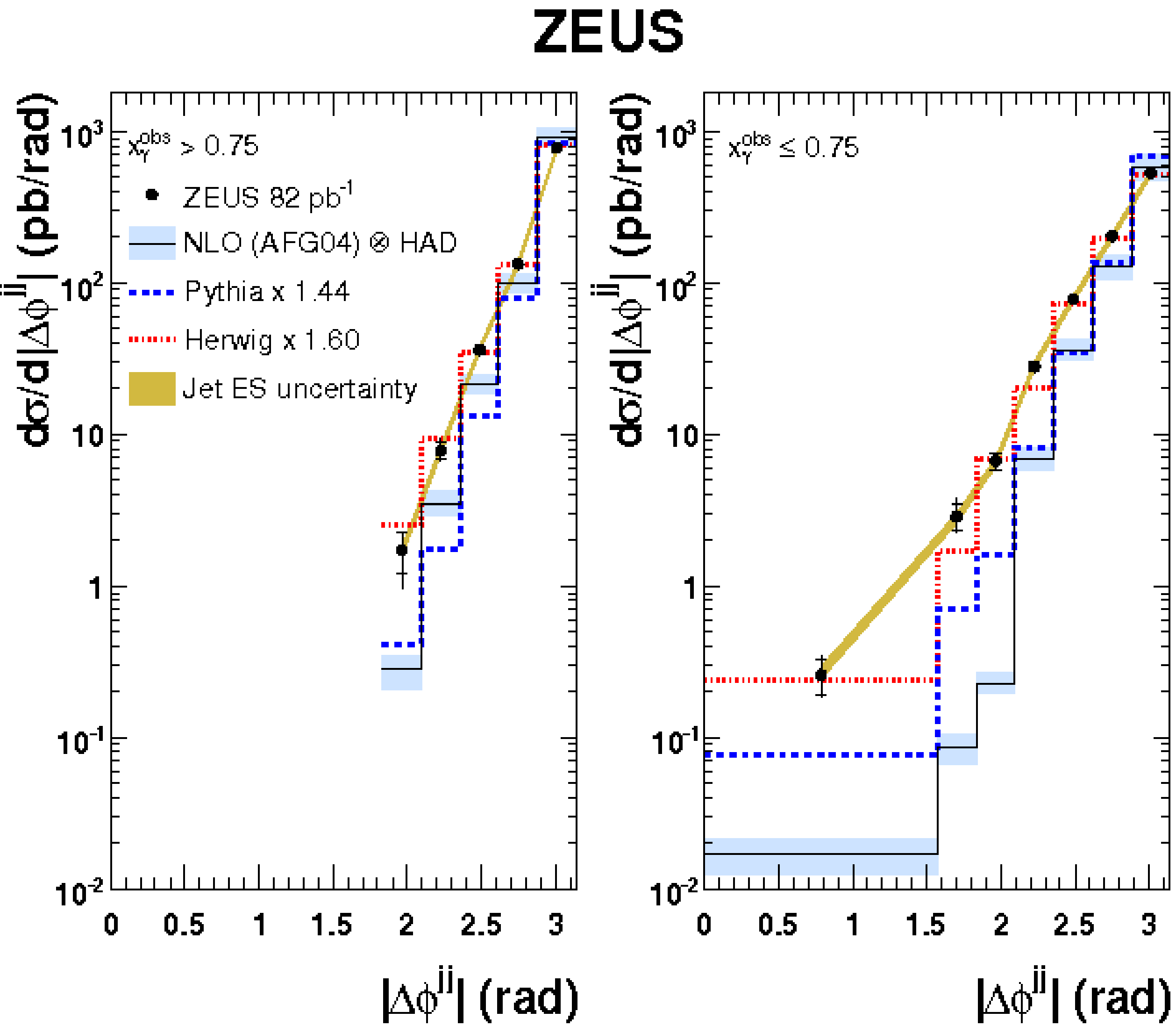



- Resolved enhanced: cross section rises more rapidly
- Confirms dominating gluon propagator

hep-ex/0603014 H1: 66.6 $pb^{-1}$, $Q2<1$ $GeV^2$, $0.1<y<0.9$, $-0.5<\eta^{jet}<2.75$, $E_T^{Jet1}>25$ GeV, $E_T^{Jet2}>15$ GeV

# Azimuthal Correlation: dσ/d|Δ^ij|




- NLO: back-to-back: well described
- LO MC: scaled

- $x_\gamma^{obs}$ >0.75: direct enhanced
  - x-sec less steep NLO and PYTHIA

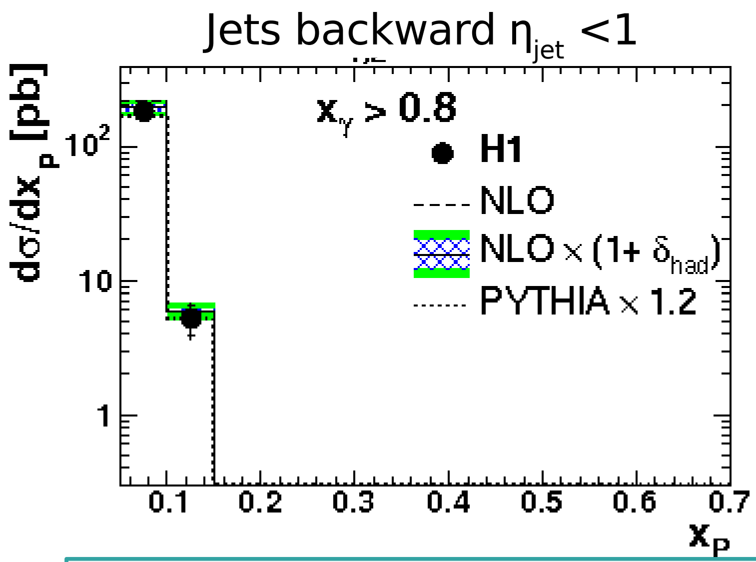
- $x_\gamma^{obs}$ <0.75: resolved enhanced
  - NLO much too steep, below the data
  - PYTHIA: poor description

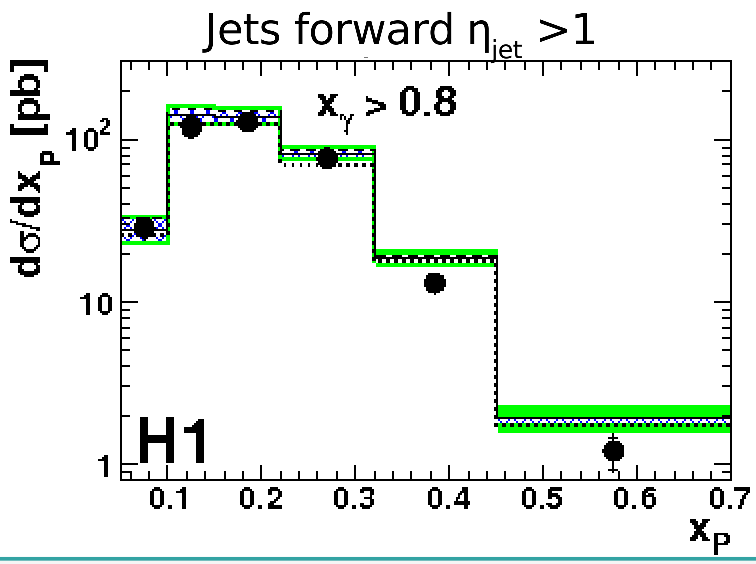
HERWIG: good description shower treatement better to account for HO effects

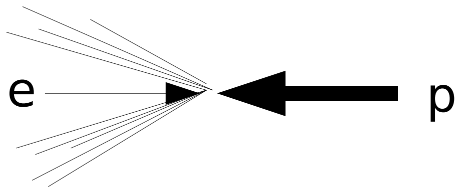
arXiv:0706.3809 [hep-ex]]  ZEUS: 81.8 pb-1, $Q^2$<1 $GeV^2$, 142<$W^{\gamma p}$<293 GeV, -1<$\eta^{jet}$<3, $E_T^{Jet1}$>20 GeV, $E_T^{Jet2}$>15 GeV

$x_p$: momentum fraction carried by parton of proton

$$x_p^{obs} = \frac{E_T^{jet1}\exp(\eta^{jet1}) + E_T^{jet2}\exp(\eta^{jet2})}{2E_p}$$



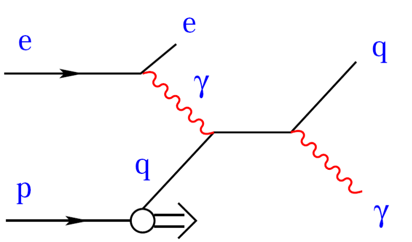



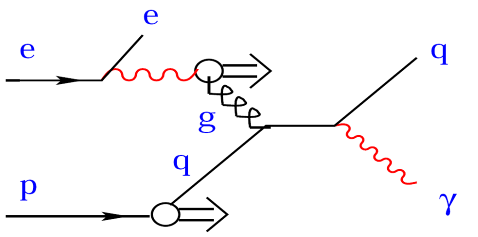

- Direct enhanced sample, results for resolved enhanced similar
- NLO, PYTHIA: overall good description, except highest $x_p$
- Forward-forward topology: access to high $x_p$
- PDF uncertainty largest for high $x_p$ (green)

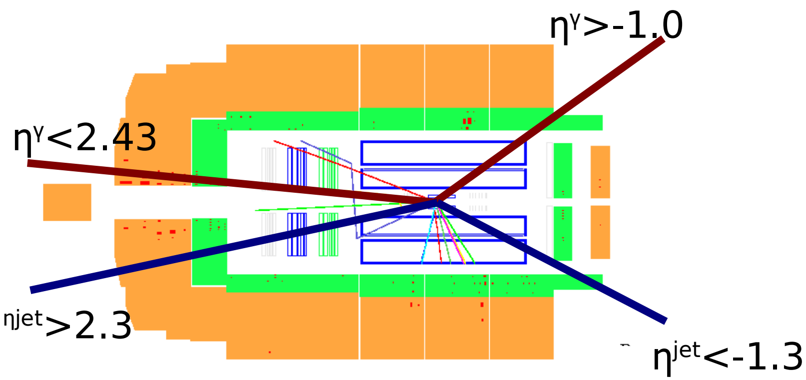
hep-ex/0603014 H1: 66.6 $pb^{-1}$, $Q2<1$ $GeV^2$, $0.1<y<0.9$, $-0.5<\eta^{jet}<2.75$, $E_T^{Jet1}>25$ GeV, $E_T^{Jet2}>15$ GeV

# Prompt Photons in Photoproduction

In addition to direct and resolved contributions: quark-to-photon fragmentation



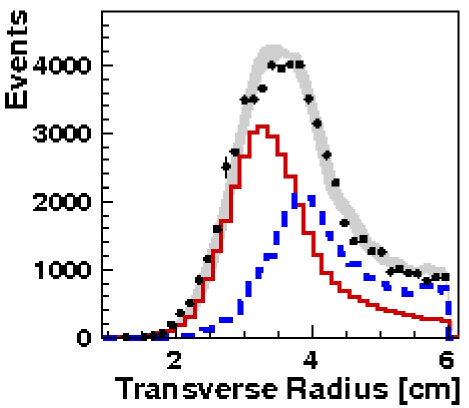



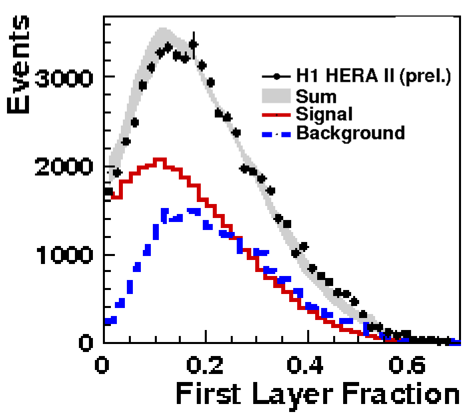

- Alternative access to $x_\gamma$ and $x_p$
- Different systematics
- Smaller corrections for hadronisation
- New analysis extends to forward region

- $6 < E_T^\gamma < 15$ GeV
- $-1.0 < \eta^\gamma < 2.43$
- $0.1 < y < 0.7$
- Isolation $z = E_T^\gamma / E_T^{photon\text{-}jet} > 0.9$

Exclusive photon plus jet

- $4.5 < E_t^{jet}$
- $-1.3 < \eta^{jet} < 2.3$

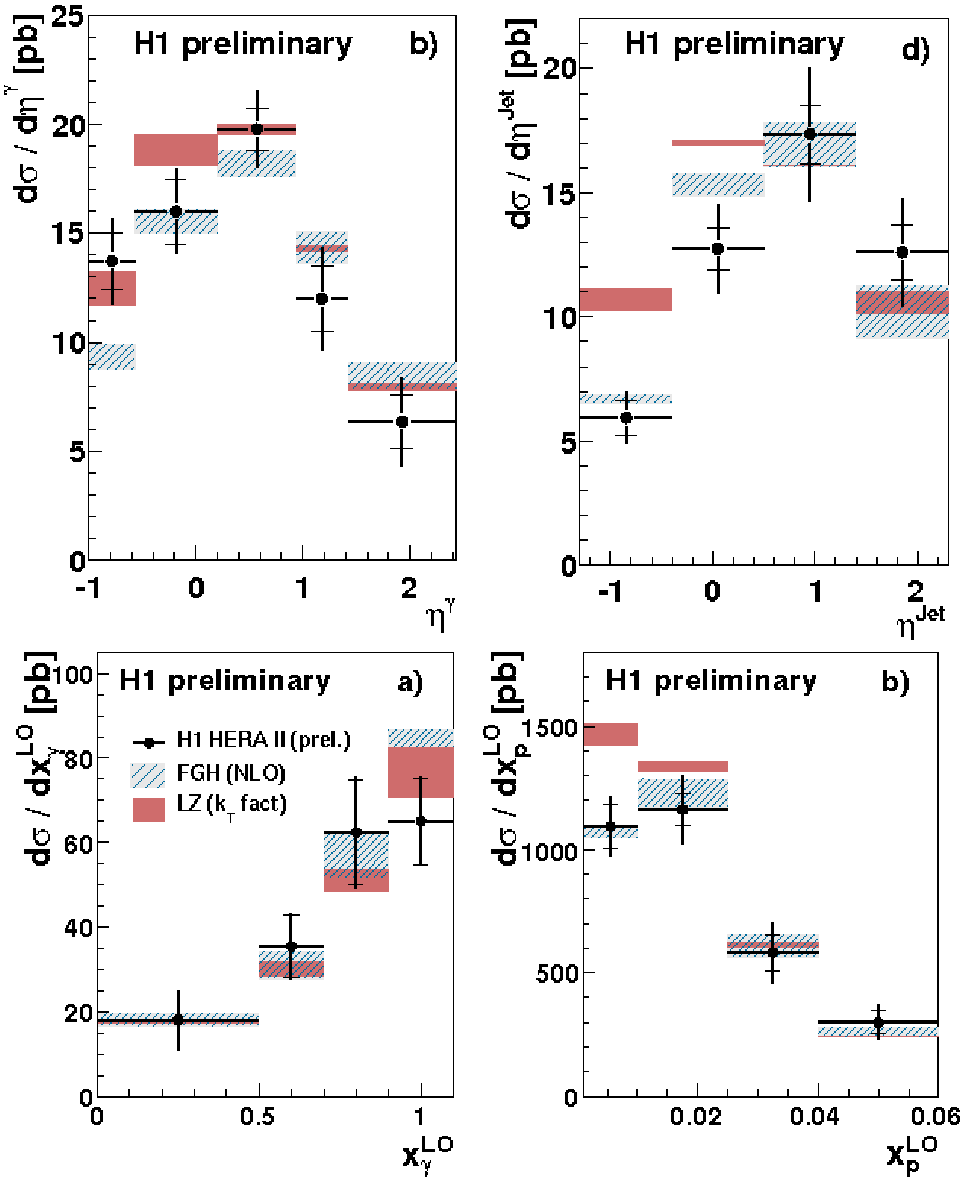



Separation from background: shower shape

H1 preliminary 09-035

# Prompt Photon plus Jet Cross Section




Comparison to
NLO calculation (FGH)
kt factorisation approach (LZ)

FGH low for backward photons
LZ does not describe the jets

$$x_{\gamma}^{LO} = E_T^{\gamma} \frac{\exp(-\eta^{\gamma}) + \exp(-\eta^{jet})}{2\, y\, E_e}$$

$$x_{p}^{LO} = E_T^{\gamma} \frac{\exp(\eta^{\gamma}) + \exp(\eta^{jet})}{2\, E_p}$$

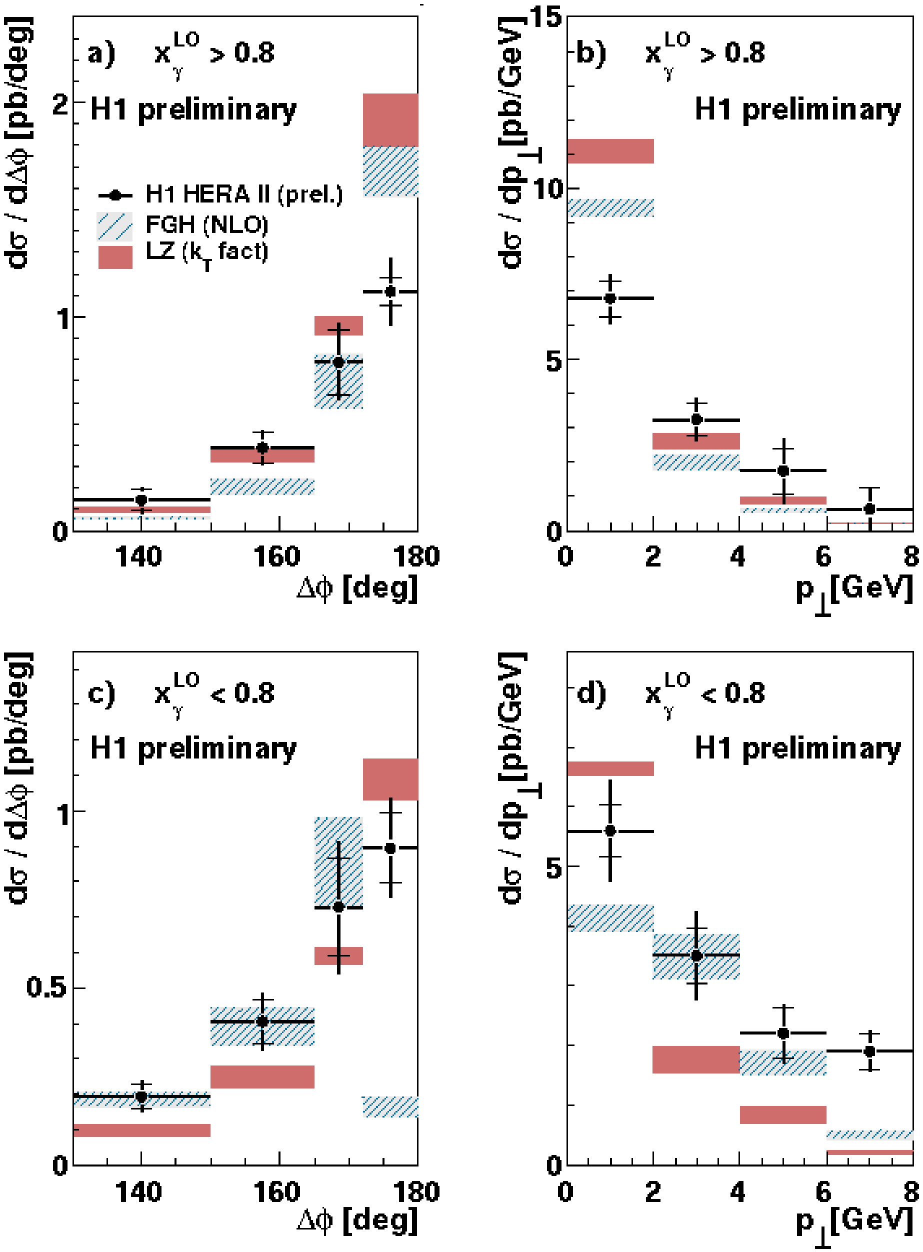
Reasonable description by the calculations
LZ problems at low $x_p$ – overshoot at low $\eta^{jet}$

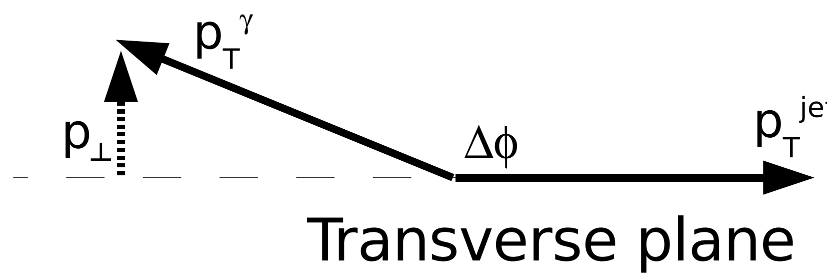
H1 preliminary 09-035 $6 < E_T^{\gamma} < 15$ GeV, $-1.0 < \eta^{\gamma} < 2.43$, $0.1 < y < 0.7$, $4.5 < E_t^{jet}$, $-1.3 < \eta^{jet} < 2.3$

# Prompt Photon and Jet: Transverse Correlation

Direct enhanced

Resolved enhanced



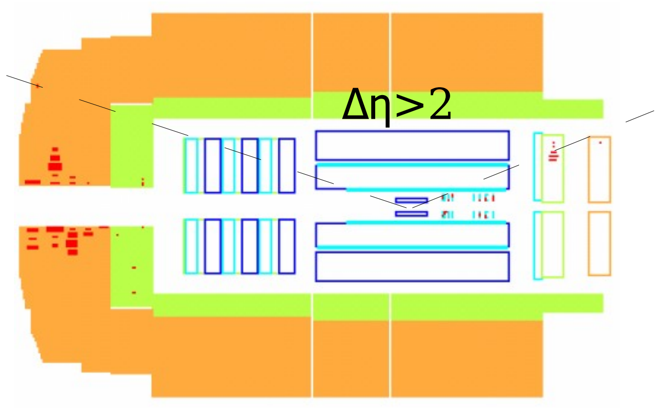




- $x_\gamma > 0.8$
  Both calculations overestimate back-to-back configuration
- $x_\gamma < 0.8$
  multiple soft gluon emission:
  NLO not valid in last bin $\Delta\Phi$
  LZ does underestimates tails

Reminder dijets:
back-to-back well described
NLO steeper than data

H1 preliminary 09-035 $6 < E_T^\gamma < 15$ GeV, $-1.0 < \eta^\gamma < 2.43$, $0.1 < y < 0.7$, $4.5 < E_t^{jet}$, $-1.3 < \eta^{jet} < 2.3$

# Diffractive Scattering of high $t$ Photons $e^+p \rightarrow e^+\gamma Y$

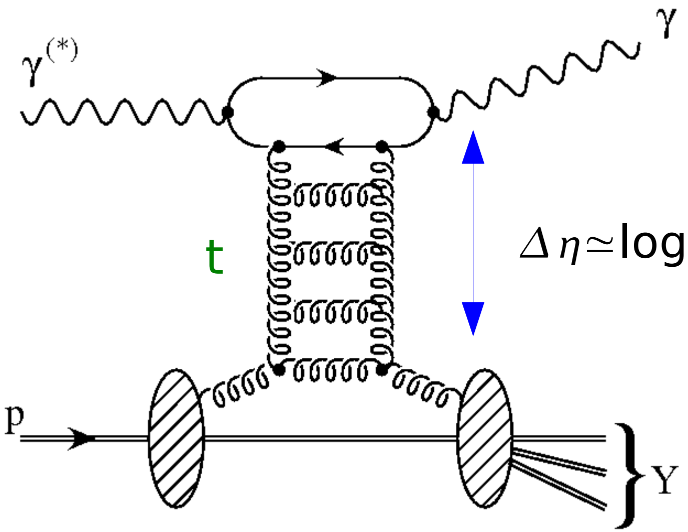



- Clean process
- Photoproduction with large $t$: hard scale
- Complements measurements with VM (J/ψ,ρ,φ)
- No VM wave function uncertainty
- Important test of the BFKL dynamics σ(W),dσ/dt
- Extends DVCS to small $Q^2$
- LLA BFKL calculation included in HERWIG

Kinematic recontruction

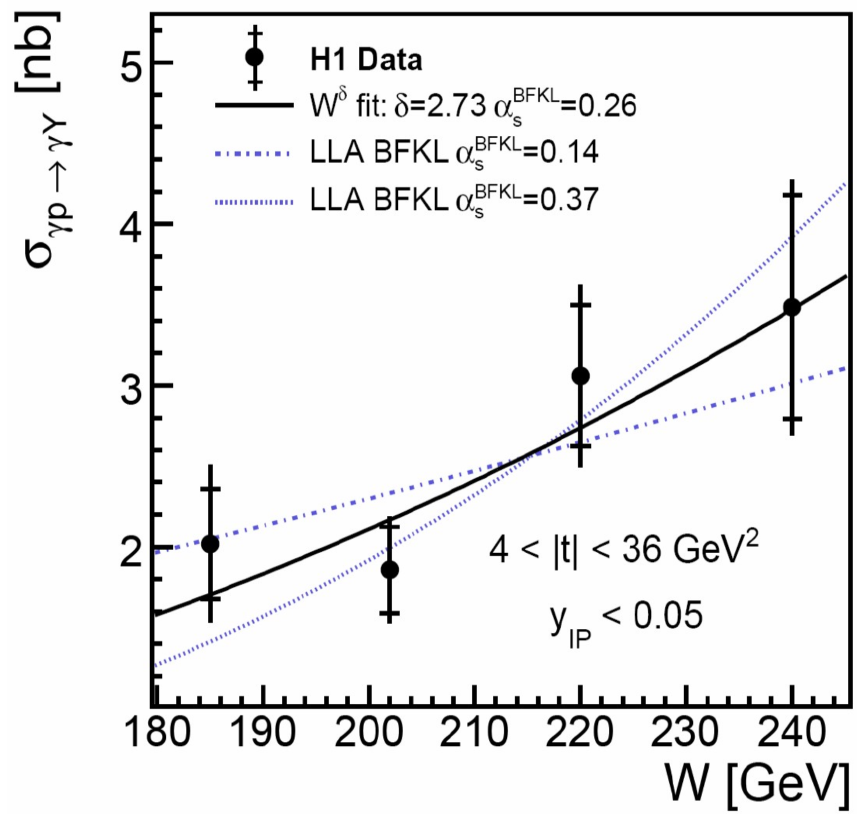
$$t = (q - p_X) \rightarrow |t| = (p_T^\gamma)^2$$

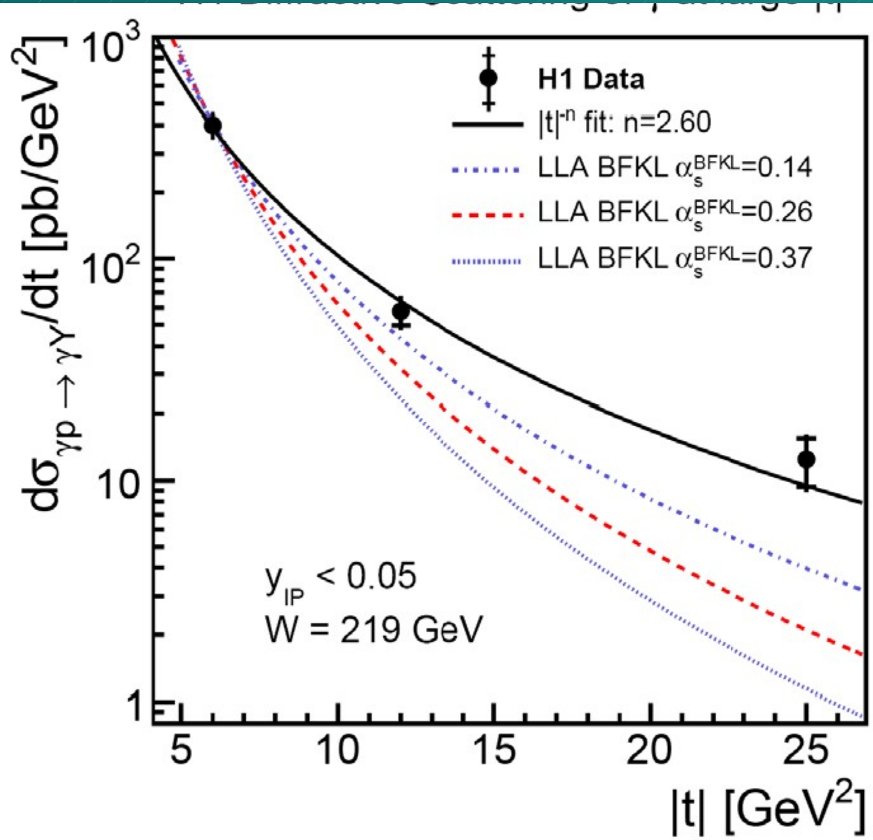
$$W^2 = (1 - \frac{E_{e'}}{E_e}) \cdot s$$




[arXiv:0706.3809 [hep-ex]] 46.2 $pb^{-1}$, $Q^2<0.01$ $GeV^2$, 175 < W < 247, 4<|t|<36 $GeV^2$, $y_{IP}<0.05$, $p_t^\gamma$ > 2 GeV, $E^\gamma$ > 8 GeV, Δη>2

# Diffractive Scattering of High $t$ Photons $e^+p \rightarrow e^+\gamma Y$




rise of $\sigma$ with W: fit: $\sigma \sim W^{\delta}$

$\delta = 2.73 \pm 1.02\ (\text{stat})\ ^{+0.56}_{-0.78}\ (\text{syst})$

$\langle t \rangle = 6.1\ \text{GeV}^2$

- $\delta$ compatible with J/Ψ data $\delta = 1.29 \pm 0.23 \pm 0.16$

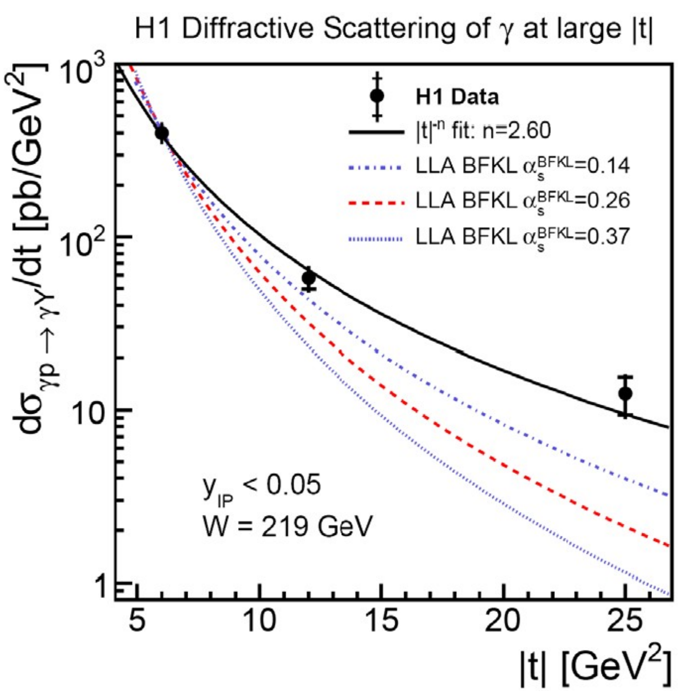
Fit: $d\sigma/dt \sim |t|^{-n}$

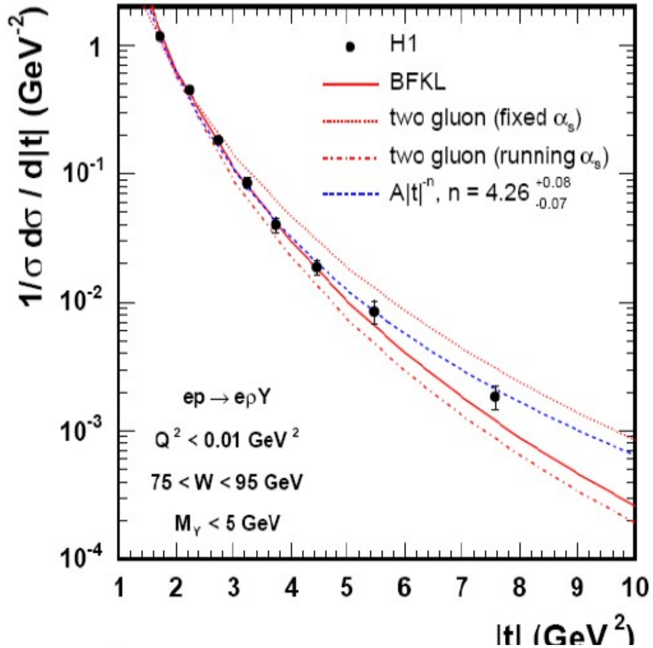
$n = 2.60 \pm 0.19(\text{stat})\ ^{+0.03}_{-0.08}\ (\text{syst})$

- $|t|$ distribution harder than LLA BFKL
- harder than for vector mesons

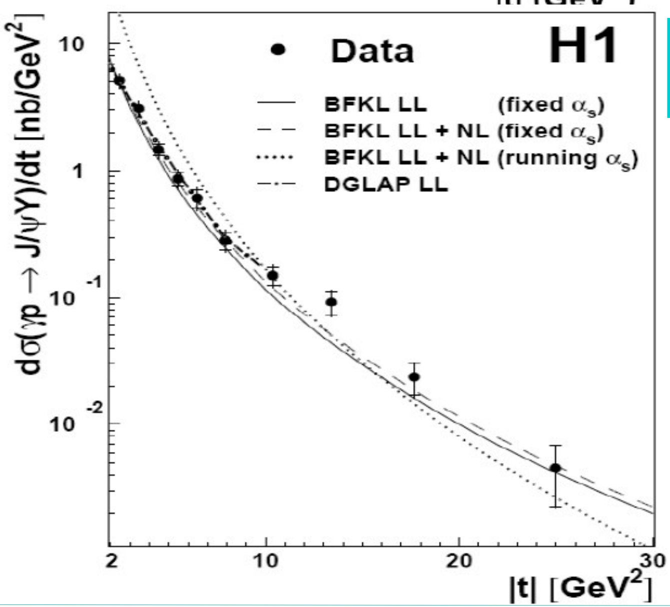
[arXiv:0706.3809 [hep-ex]] 46.2 $pb^{-1}$, $Q^2 < 0.01\ \text{GeV}^2$, $175 < W < 247$, $4 < |t| < 36\ \text{GeV}^2$, $y_{IP} < 0.05$, $p_t^{\gamma} > 2$ GeV, $E^{\gamma} > 8$ GeV, $\Delta\eta > 2$

# Comparison with ρ and J/ψ at high /t/




ρ




J/ψ

dσ/dt $\sim |t|^{-n}$

Photons: n=2.60 ± 0.19(stat) $^{+0.03}_{-0.08}$ (syst)

ρ: n= $4.26^{+0.08}_{-0.07}$

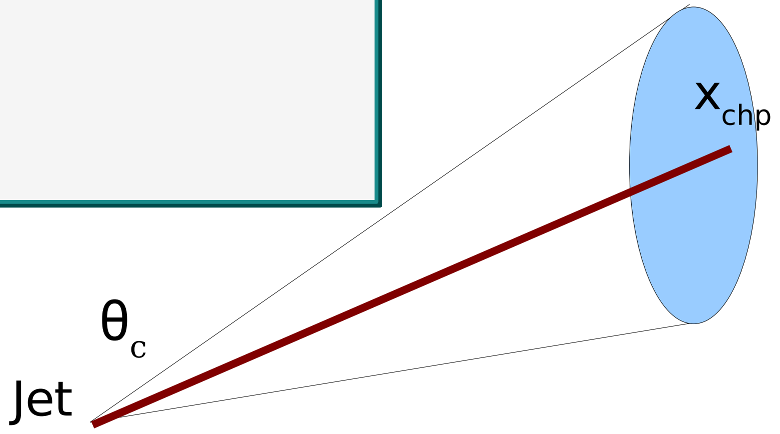
J/ψ n= 3.78 ±0.17±0.06

harder than for J/Ψ or ρ

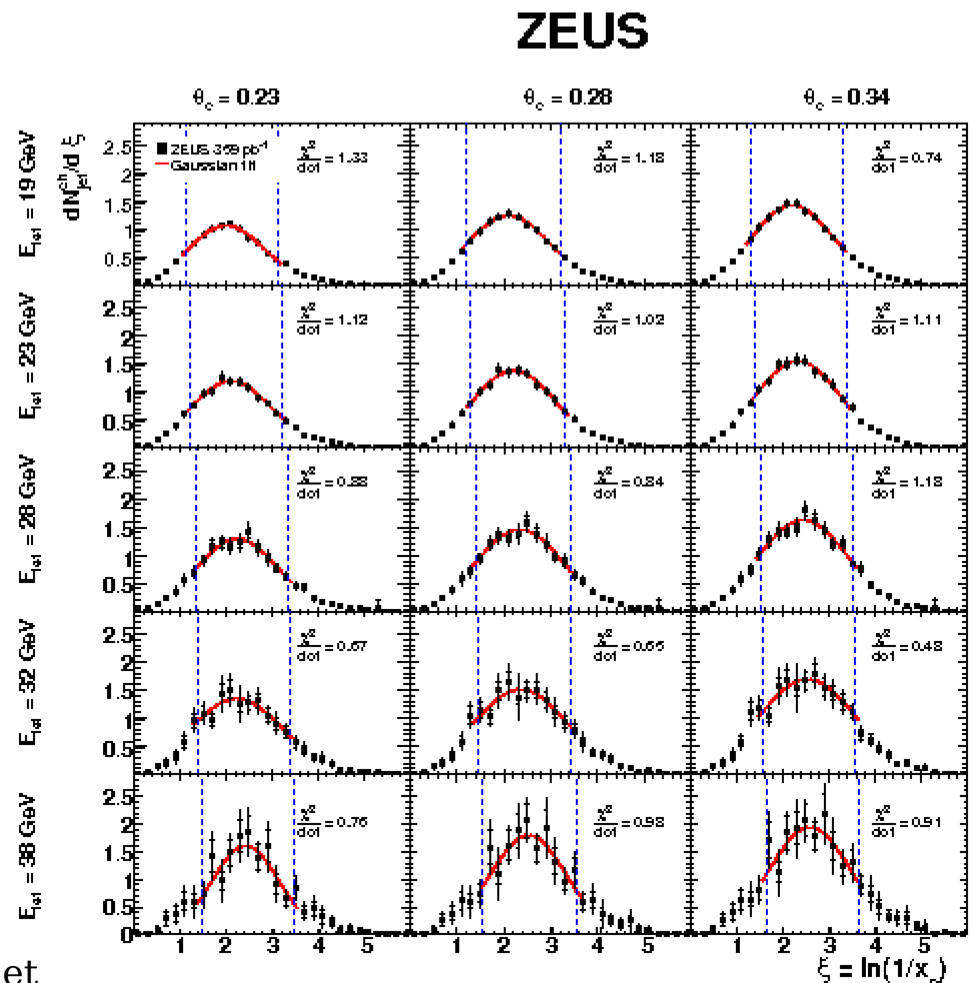
[arXiv:0706.3809 [hep-ex]] 46.2 $pb^{-1}$, $Q^2<0.01$ $GeV^2$, 175 < W < 247, 4<|t|<36 $GeV^2$, $y_{IP}<0.05$, $p_t^{\gamma} > 2$ GeV, $E^{\gamma} > 8$ GeV, Δη>2

# Soft Particle Distribution in Photoproduction

- Study fragmentation of jets
  non perturbative region of QCD
- Charged particles in jets: tracks with
  $p_t$>0.15 GeV $|\eta|$<1.7
- Prediction MLLA
  Modified leading log approximation
  includes all terms of $\alpha_s^n \log^{2n}(E_{init}^{pl})$ and $\alpha_s^n \log^{2n-1}(E_{init}^{pl})$
  describes momentum and multiplicity spectra of partons
  accounts for colour-coherence (angular ordering scheme)
  free parameter
    - $\Lambda_{eff}$ effective energy scale, $Q_0=\Lambda_{eff}$ : lowest valid scale
- Scaled momentum variable $\xi(\theta_c, E^{jet})$
  $\xi = \ln(1/x_{chp})$
  $x_{chp}$:fraction of jet momentum




ZEUS arXiv:0904.3466v1 [hep-ex]




$E^{jet}$

opening angle $\theta_c$

$\xi(\theta_c, E^{jet})$ $\xi = \ln(1/x_{chp})$

$x_{chp}$:fraction of jet momentum

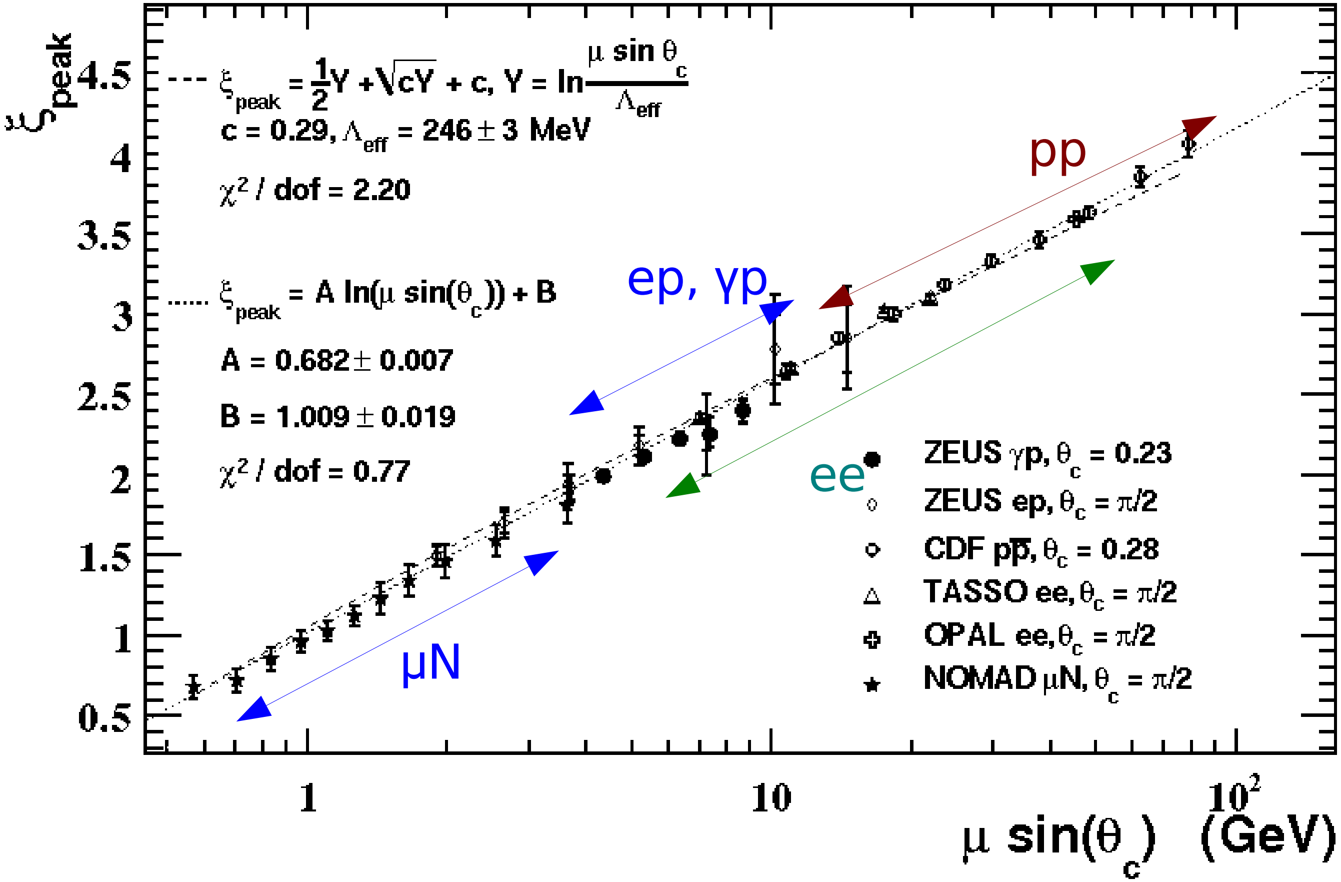
- similar in shape
- roughly Gaussian, upper tails
- Shape predicted by MLLA
- Fit: gaussian and MLLA

- 2005-2007, 359 $pb^{-1}$
- $0.2 \leq y_{jb} \leq 0.85$
- two jets with $|\eta_{jet}| \leq 1$
  $E_t^{jet1} \geq 17$ GeV, $E_t^{jet2}/E_t^{jet1} \geq 0.8$
  back-to-back $|\Phi^{jet1}-\Phi^{jet2}| \geq 0.9\pi$
- $x_\gamma^{obs} \geq 0.75$
- Tracks $p_t > 0.15$ GeV $|\eta| < 1.7$

ZEUS arXiv:0904.3466v1 [hep-ex]

# Scaled Momentum Distributions

$\xi_{peak}$ vs μ sin($\theta_c$), μ=$E^{jet}$ characteristic energy scale




- $\xi_{peak} \approx A \cdot \ln(\mu \sin(\theta_c)) + B$
- MLLA small correction
- ZEUS γp alone below global fit
- MLLA fit: $\Lambda_{eff}$
  $\Lambda_{eff}$ lowest valid scale
- Slight dependence on $\theta_c$
- No dependence on energy

$\Lambda_{eff}$ =values largely consistent with other experiments

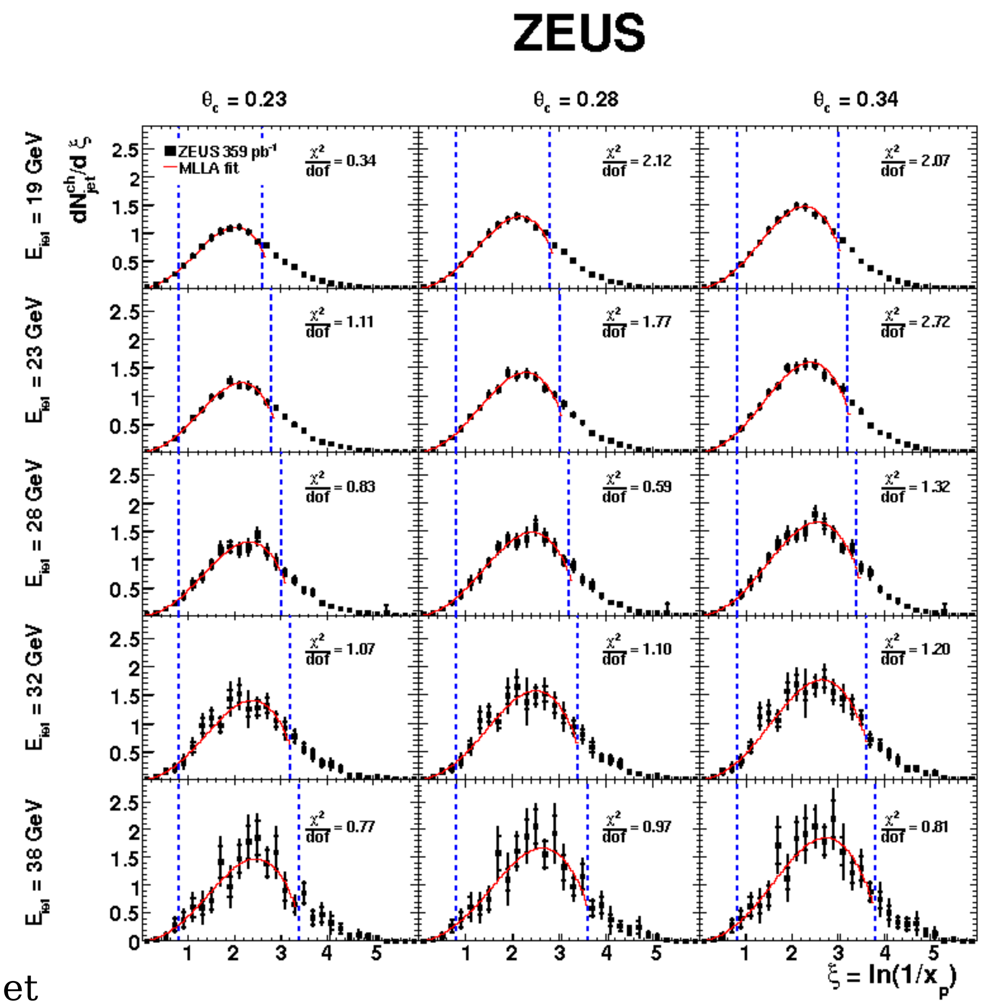
ZEUS arXiv:0904.3466v1 [hep-ex]

# Summary

- Dijets in photoproduction
  many QCD tests
  Sensitivity to photon and proton PDF
  well described by NLO calculation
  except azimuthal correlations
- Prompt photons in photoproduction
  NLO calculation and calculation based on kt factorisation
  description reasonably well
  problems in some kinematic regions
- Diffractive scattering of high $|t|$ photons
  $|t|$ dependence harder than expected from BFKL or VM production
- Scaled momentum distributions
  in agreement with MLLA with a universal scale $\Lambda_{eff}$

# Backup slides

## Charged Particles in Dijet Events




$E^{jet}$

opening angle $\theta_c$

ZEUS preliminary

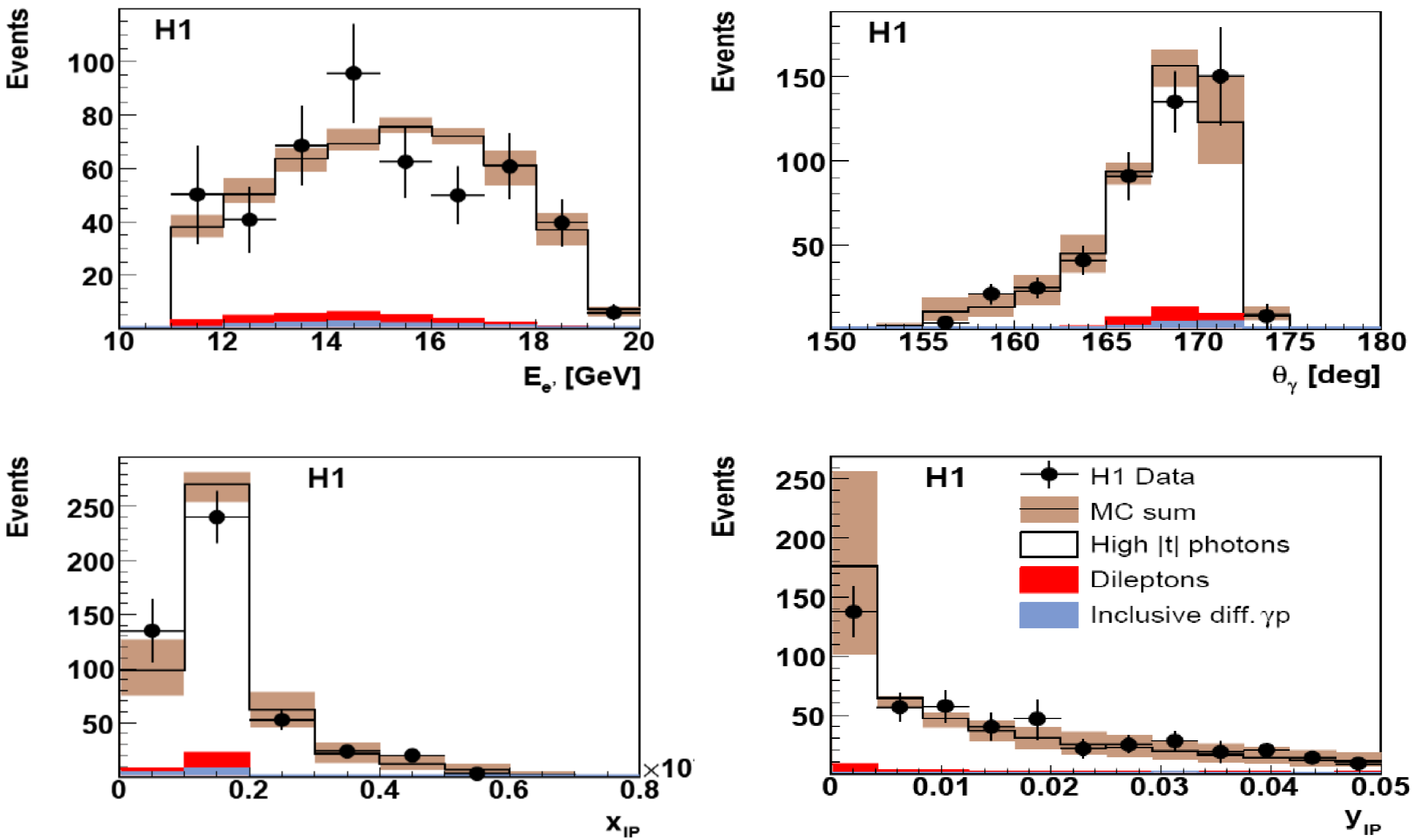
$\xi(\theta_c, E^{jet})$ $\xi = \ln 1/x_p$

$x_p$:fraction of jet momentum

- similar in shape
- roughly Gaussian, upper tails
- Shape predicted by MLLA
- Fit: gaussian and MLLA

- 2005-2007, 359 $pb^{-1}$
- $0.2 \leq y_{jb} \leq 0.85$
- two jets with $|\eta_{jet}| \leq 1$
  $E_t^{jet1} \geq 17$ GeV, $E_t^{jet2}/E_t^{jet1} \geq 0.8$
  back-to-back $|\Phi^{jet1} - \Phi^{jet2}| \geq 0.9\pi$
- $x_\gamma^{obs} \geq 0.75$
- Tracks $p_t > 0.15$ GeV $|\eta| < 1.7$

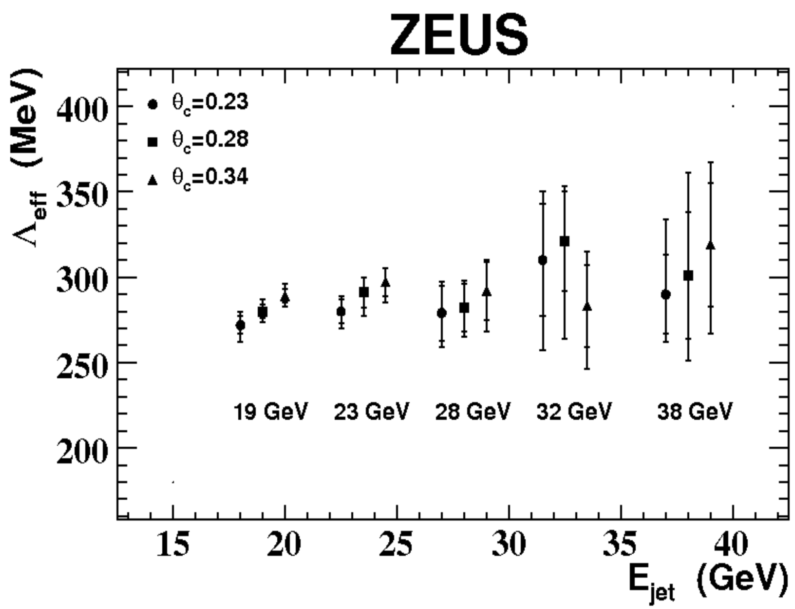
# Diffractive Scattering of high t Photons

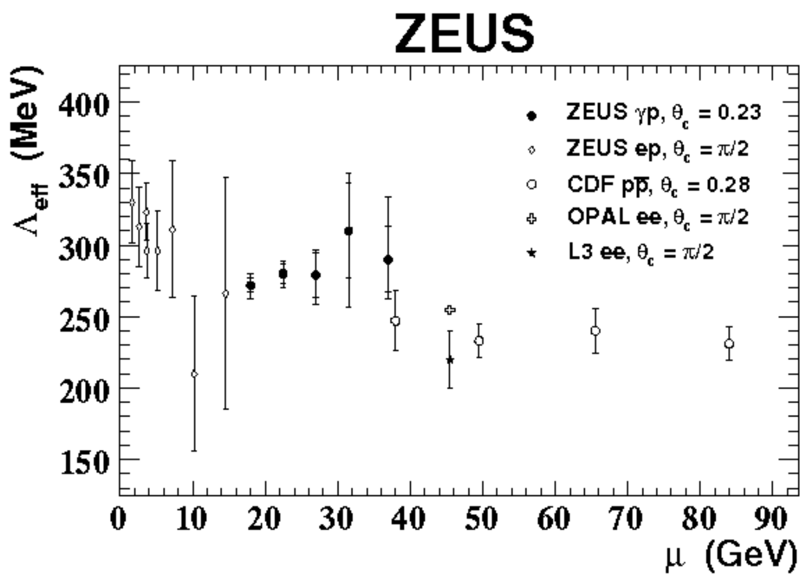



[arXiv:0706.3809 [hep-ex]]

# Scaled Momentum Distributions

## Charged Particles in Dijet Events




$\Lambda_{eff}$ from $\xi_{peak}$

$$\sigma_{peak} = \frac{1}{2} + \sqrt{cY} - c \quad c = 0.29$$

$$Y = \ln(E \sin(\Theta_c) / \Lambda_{eff})$$

- MLLA fit: $\Lambda_{eff}$
  $\Lambda_{eff}$ lowest valid scale

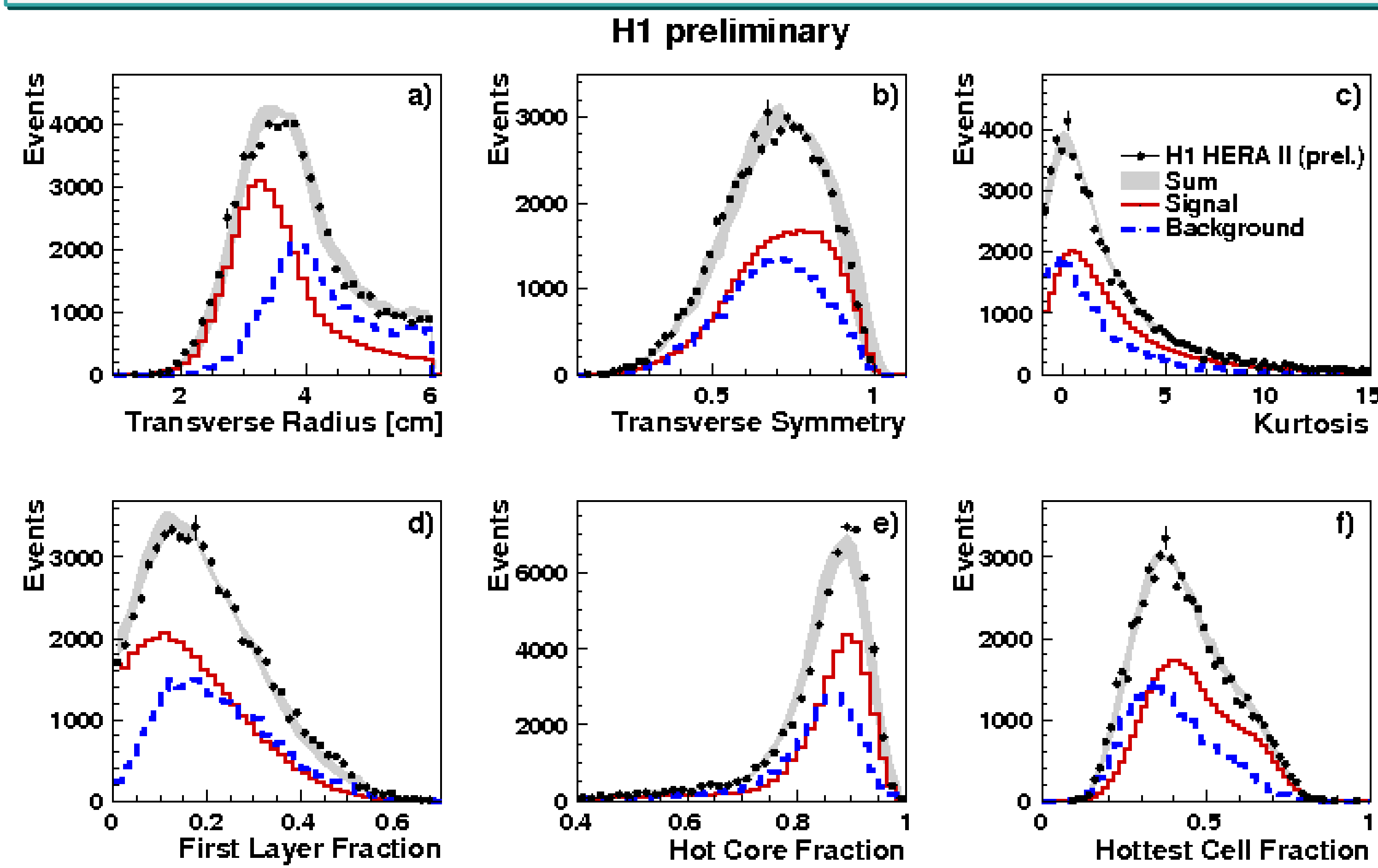
- Slight dependence on $\theta_c$
- No dependence on energy

$\Lambda_{eff}$ =values largely consistent with other experiments

ZEUS preliminary

# Prompt Photons in Photoproduction

- Alternative access to $x_\gamma$ and $x_p$
- Different systematics, smaller corrections for hadronisation
- New analysis extends to forward region
- Large background from neutral mesons




Shower shapes

Discriminator

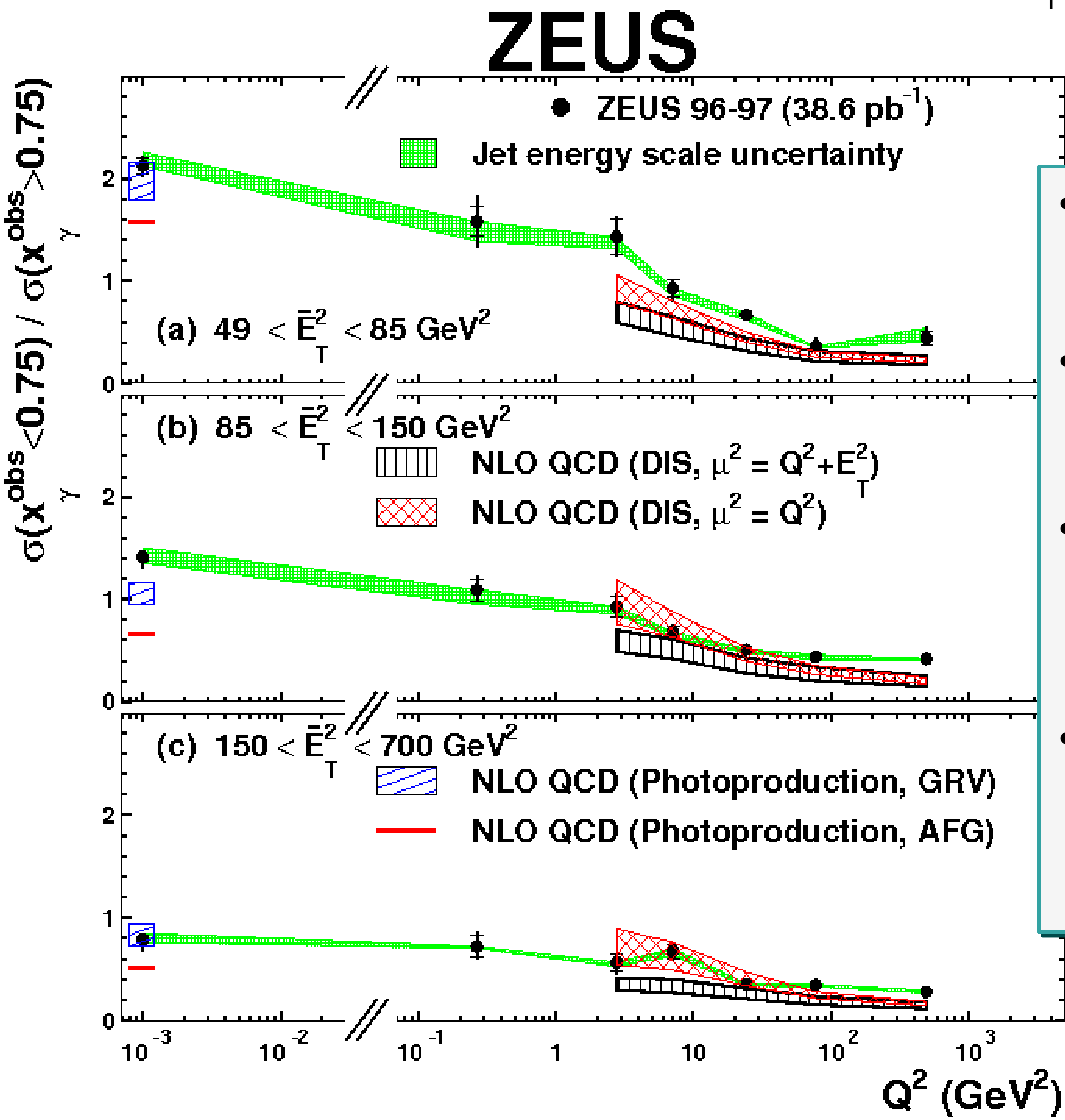
Unfold signal

Cross Sections

H1 preliminary 09-035 $6<E_T^\gamma < 15$ GeV, $-1.0<\eta^\gamma<2.43$, $0.1<y<0.7$, $4.5< E_t^{jet}$, $-1.3<\eta^{jet}<2.3$

# Resolved component, R=$\sigma(x_\gamma^{obs}<0.75)/\sigma(x_\gamma^{obs}>0.75)$

Ratio R as a function of $Q^2$ for different $E_T^2$




- Several experimental and theoretical uncertainties cancel
- Supression of resolved component with $Q^2$ and $E_T^2$
- NLO calculations for $Q^2 \approx 0$
  AFG underestimates resolved cont.
  GRV reasonable description
- NLO calculation for $Q^2>0$
  scale $Q^2$ preferred
  some suppression visible

hep-ex/0404033 ZEUS: 38.6 $pb^{-1}$ ,$0<Q^2<2000$ $GeV^2$ jets: $-3<\eta^{\gamma p}<0$ , $E_T^{Jet1}>7.5$ GeV, $E_T^{Jet2}>6.5$ GeV